

Observations of the post shock break-out emission of SN 2011dh with *XMM-Newton*[★]

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ABSTRACT

Context. After the occurrence of the type cIIb SN 2011dh in the nearby spiral galaxy M 51 numerous observations were performed with different telescopes in various bands ranging from radio to γ -rays.

Aims. We analysed the *XMM-Newton* and *Swift* observations taken 3 to 30 days after the SN explosion to study the X-ray spectrum of SN 2011dh.

Methods. We extracted spectra from the *XMM-Newton* observations, which took place ~ 7 and 11 days after the SN. In addition, we created integrated *Swift*/XRT spectra of 3 to 10 days and 11 to 30 days.

Results. The spectra are well fitted with a power-law spectrum absorbed with Galactic foreground absorption. In addition, we find a harder spectral component in the first *XMM-Newton* spectrum taken at $t \approx 7$ d. This component is also detected in the first *Swift* spectrum of $t = 3 - 10$ d.

Conclusions. While the persistent power-law component can be explained as inverse Compton emission from radio synchrotron emitting electrons, the harder component is most likely bremsstrahlung emission from the shocked stellar wind. Therefore, the harder X-ray emission that fades away after $t \approx 10$ d can be interpreted as emission from the shocked circumstellar wind of SN 2011dh.

Key words. Shock waves – circumstellar matter – X-rays – supernovae: individual: SN2011dh

1. Introduction

Massive stars at the end of their lives have undergone phases of more or less strong mass loss. The evolution of the stars and thus also the way their supernovae (SNe) evolve, depend strongly on their mass loss rates. The interaction of the SN shock wave with the stellar wind creates a hot region around the SN site, in which electrons are accelerated and produce radio synchrotron emission. The hot plasma around the SNe can be observed in X-rays. Strong X-ray emission is in particular expected when the SN shock wave breaks out of the star and starts propagating into the circumstellar material (Chevalier & Irwin 2011, 2012, and references therein). Owing to prompt observations with the *Swift* or the *Chandra* telescope, X-rays from the interaction of the SN shock with the circumstellar matter have been detected for a number of SNe (e.g., SN 2006jc or SN 2010jl, Immler et al. 2008; Chandra et al. 2012, respectively). Soderberg et al. (2008) detected a transient X-ray source with *Swift*, which was then identified as SN 2008D in the galaxy NGC 2770. The X-ray outburst was ascribed to the shock break-out of the SN.

On May 31, 2011, a supernova explosion was observed (Silverman et al. 2011) in the nearby galaxy M51 located at a distance of 8.4 ± 0.7 Mpc (Vinkó et al. 2012). It was classified as a type IIb SN (Arcavi et al. 2011a). Several radio, optical, and X-ray observations followed to study the SN evolution, which also allowed to constrain the nature of the progenitor suggesting a compact progenitor star with a radius of $\sim 10^{11}$ cm and thus

the classification of SN 2011dh as a type cIIb SN (Arcavi et al. 2011b; Soderberg et al. 2012).

Soderberg et al. (2012) studied SN 2011dh using *Swift* and *Chandra* data in X-rays and the Submillimeter Array, the Combined Array for Research in Millimeter-wave Astronomy, and the Expanded Very Large Array in radio in the following weeks. They showed that the observed radio emission is synchrotron radiation of electrons, accelerated in the forward shock of the SN explosion, while inverse Compton (IC) scattering of these electrons produced X-rays. They estimated that the break-out of the shock out of the compact progenitor must have occurred at $R_{br} \approx 4 \times 10^{11}$ cm with a rise time for the break-out pulse of $t_{br} \approx 1$ min. However, the shock break-out pulse was not detected by any X-ray or γ -ray observatory.

We report the detection of a hard X-ray component in the early spectra of SN 2011dh observed with *XMM-Newton* and *Swift*. The comparison of the spectra taken at different times after the SN event ranging from $t = 3$ to 30 d allow us to consider this component as emission from the interaction of the SN shock with the circumstellar material in the immediate surroundings of the progenitor star.

2. Data

2.1. *XMM-Newton* data

Shortly after SN 2011dh occurred, two observations with *XMM-Newton* were initiated. The first observation with the ObsID 0677980701 was performed at $t \approx 7$ d after the SN explosion from 2011/06/07, 5:19:56 to 2011/06/07, 8:30:40 (UTC) with an exposure of ~ 11 ks. All European Photon Imaging Cameras (EPICs, Strüder et al. 2001; Turner et al. 2001) were operated in

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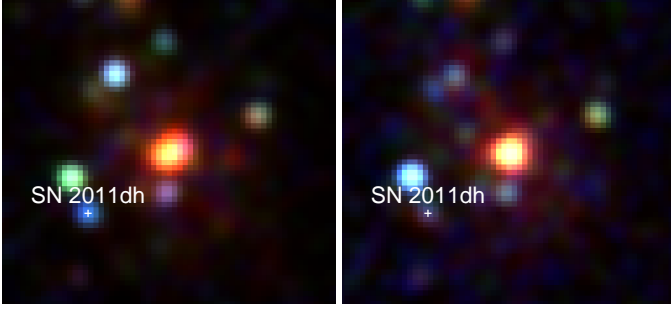


Fig. 1. XMM-Newton EPIC-pn images ~ 7 d (left) and ~ 11 d (right) after the SN explosion in the colours red (0.3 – 1.0 keV), green (1.0 – 2.0 keV), and blue (2.0 – 8.0 keV).

full-frame mode and used with the thin filter. The next observation took place from 2011/06/11, 5:05:03 to 2011/06/11, 8:15:38 (UTC) at $t \approx 11$ d with ~ 10 ks exposure. The EPICs were used in the same configuration as in the observations before. After filtering good time intervals, only 4 and 2.6 ks of useful data remained for the observations 0677980701 and 0677980801, respectively.

Due to low statistics, the MOS1/2 data are not useful for further analysis. Therefore, we created images from the EPIC-pn data in the bands 0.3 – 1.0 keV, 1.0 – 2.0 keV, and 2.0 – 8.0 keV (Fig. 1). As can be seen in the EPIC-pn images, the X-ray source at the position of SN 2011dh is brighter on 2011/06/07 than on 2011/06/11 and also appears more blueish. The red-orange appearing source in the center is the nucleus of M 51 together with an unresolved ultra-luminous X-ray source (ULX). The other brighter blue or green sources are also ULXs in M 51 (Dewangan et al. 2005).

We extracted EPIC-pn spectra of SN 2011dh in a circular region with a radius of $20''$ around the optical position. The background spectrum was extracted in a $30''$ radius circle close to the source, where no X-ray source was detected. Hereafter, we call the EPIC-pn spectrum of 2011/06/07 spectrum XMM1 and that of 2011/06/11 spectrum XMM2.

2.2. Swift data

SN 2011dh was also observed with the Swift satellite in a large number of observations to study the evolution of the X-ray emission. Soderberg et al. (2012) derived the X-ray fluxes of SN 2011dh from Swift observations taken with the X-ray telescope (XRT) from 2011/06/03 to 29 and analysed the integrated spectrum from the observations of 2011/06/03 to 17. Since we would like to study the Swift spectra at times comparable to the XMM-Newton observations, we collected XRT observations of SN 2011dh starting ~ 3 d after the SN explosion, in the time period from 2011/06/03 12:04:02 (UT) to 2011/06/10 17:08:32 (total exposure time of ~ 44 ks) and in a later period from 2011/06/11 04:55:01 to 2011/06/30 12:33:50 (total exposure time of ~ 85 ks). The XRT data obtained in photon-counting (PC) mode were processed with the standard procedures (XRTPIPELINE v.0.12.6, Burrows et al. 2005). Standard grade filtering (0 – 12) and screening criteria were applied.

Events for the spectral analysis were accumulated within the same circular regions as for the XMM-Newton spectra, i.e., with $20''$ radius centered on the optical position of the SN for the source spectrum and from a source-free circular region of radius $30''$ close to the SN for the background. We used version v.013 of the response matrices in HEASARC calibration database

(CALDB) and the corresponding ancillary response files created using the task XRTMKARF. We call the integrated spectrum of 2011/06/03 to 10 spectrum Swift1 and that of 2011/06/11 to 30 spectrum Swift2.

3. Spectral analysis

The spectrum Swift1 is merged from the data of 2011/06/03 to 10 and thus represents an average spectrum of before 2011/06/10. Similarly, spectrum Swift2 is an average spectrum of after 2011/06/11. Therefore, the four analysed spectra have the following chronological order: Swift1, XMM1, XMM2, and Swift2, with Swift1 and XMM1 corresponding to spectra taken at similar times.

3.1. The longer persistent soft X-ray emission

We analysed the two XMM-Newton and two Swift spectra simultaneously to search for changes in the spectral components. Pooley (2011) reported that the Chandra spectrum taken on 2011/06/12 can be fitted with a power-law spectrum with a photon index of $\Gamma = 1.4 \pm 0.3$, absorbed by the Galactic foreground $N_H = 1.8 \times 10^{20} \text{ cm}^{-2}$. For the Swift spectra from 2011/06/03 to 17, Soderberg et al. (2012) determined a photon index of $\Gamma = 0.9 - 1.8$. We therefore fitted the spectra first with a single power-law model, also assuming foreground absorption by Galactic $N_H = 1.8 \times 10^{20} \text{ cm}^{-2}$. The first two spectra Swift1 and XMM1 can be fitted with a lower photon index of $\Gamma = 1.1$ ($1.0 - 1.3$)¹ with red. $\chi^2 = 1.1$ and d.o.f. = 33, whereas the spectra XMM2 and Swift2 taken after 2011/06/11 are fitted well with $\Gamma = 1.8$ ($1.5 - 2.0$) with red. $\chi^2 = 1.1$ and d.o.f. = 23. Therefore, the spectra taken on the first ~ 10 days after the SN is significantly different than the spectra thereafter.

We also fitted all spectra with a single thermal bremsstrahlung model. While the temperatures fitted for the first two spectra ($t < 10$ d) are unconstrained ($kT_{\text{brems,Swift1}} > 9$ keV and $kT_{\text{brems,XMM1}} > 22$ keV, respectively), the two later spectra ($t > 11$ d) are both fitted well with temperatures of $kT_{\text{brems,XMM2}} = 3(1 - 18)$ keV and $kT_{\text{brems,Swift2}} = 3(2 - 8)$ keV (red. $\chi^2 = 1.1$ at d.o.f. = 56).

3.2. The fading hard X-ray emission

A likely origin of the additional harder component in the earlier spectra is free-free emission from the shocked circumstellar wind (Chevalier & Fransson 2003). If we keep the power-law component and include an additional free-free emission component for the earlier spectra Swift1 and XMM1, the photon indices of their power-law component become higher with $\Gamma = 2.0$ ($1.6 - 2.5$) (red. $\chi^2 = 1.1$ at d.o.f. = 32). Moreover, we obtain an additional absorbing column density of $N_{\text{Hintr}} = 7.2$ ($1.3 - 15.0$) $\times 10^{20} \text{ cm}^{-2}$. The flux of the power-law component is the same for all four spectra with the unabsorbed flux being $F_{\text{pow}}(0.3 - 8.0 \text{ keV}) = 1.1(0.8 - 1.5) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$. The temperature of the bremsstrahlung component is not well constrained and we can only determine a lower limit of $kT_{\text{brems}} > 42$ keV. Figure 2 shows the confidence contours for the parameters kT_{brems} and Γ . The unabsorbed flux of the bremsstrahlung component is $F_{\text{brems}}(0.3 - 8.0 \text{ keV}) = 1.3(0.9 - 1.7) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ and $1.1(0.7 - 1.6) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ for Swift1 and XMM1, i.e., for $t < 10$ d

¹ All errors in this paper given in brackets are 90% confidence ranges.

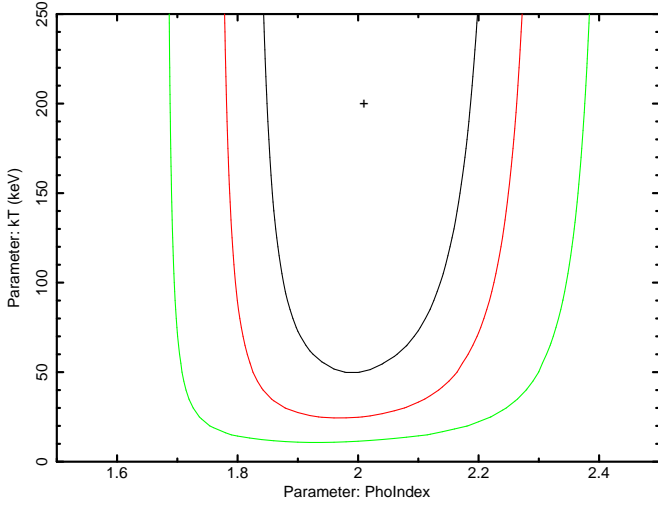


Fig. 2. Confidence level contours (63, 90, and 99%) for the parameters kT_{brems} and Γ .

and $t = 7$ d, respectively. While this component has disappeared at $t = 11$ d with an upper limit of the unabsorbed flux of $F_{\text{brems}}(0.3 - 8.0 \text{ keV}) < 0.6 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$, the power-law component seems to represent emission that is persistent up to 30 d or longer. Figure 3 shows the first two spectra Swift1 and XMM1 with a model consisting of a bremsstrahlung and a power-law component (upper diagram), while the later spectra XMM2 and Swift2 are shown with the single power-law fits (lower diagram).

Immler & Lewin (2003) on the other hand discuss the presence of a blackbody continuum of the shocked hot circumstellar gas. If we fit the spectra Swift1 and XMM1 with a blackbody model for the additional hard component we obtain a temperature of $kT_{\text{BB}} = 1.6(1.7 - 2.8) \text{ keV}$. The luminosities are $L_{\text{BB}}(< 10 \text{ d}) = 1.6(0.8 - 3.7) \times 10^{39} \text{ erg s}^{-1}$ and $L_{\text{BB}}(7 \text{ d}) = 1.6(0.8 - 3.1) \times 10^{39} \text{ erg s}^{-1}$ for Swift1 and XMM1, respectively. From the fits of the spectra XMM2 and Swift2, we obtain the following upper limits: $L_{\text{BB}}(11 \text{ d}) < 0.8 \times 10^{39} \text{ erg s}^{-1}$ and for XMM1, $L_{\text{BB}}(11 - 30 \text{ d}) < 0.3 \times 10^{39} \text{ erg s}^{-1}$.

4. Discussion

Many SNe show a softening of their X-ray spectrum days to months after the SN event (e.g., Immler & Kuntz 2005, and references therein). If the X-ray emission is mainly due to IC process as proposed for SN 2011dh by Soderberg et al. (2012), one expects $dL_X/dE \propto E^{-(p-1)/2}$, with p being the spectral index of the energy of the injected electrons responsible also for the radio synchrotron emission (e.g., Chevalier et al. 2006). This, of course, is based on a simple assumption that the particle spectrum does not change over a broad spectral range. In reality, some acceleration processes or particle losses can modify the spectrum. As the power-law fits of XMM1 and Swift1 vs. Swift2 and XMM2 have shown the photon indices are significantly different ($\Gamma = 1.1 [1.0 - 1.3]$ and $1.8 [1.5 - 2.0]$, respectively) and indicate temporal change in the X-ray spectrum. Assuming that the particle spectrum does not change its shape significantly, the softening of the X-ray spectrum is most likely not caused by the change of the slope of the non-thermal spectrum, but rather by the change of the emission components. The X-ray emitting gas behind the blast wave of the SN shock is expected to have high temperatures of 100 keV or higher, while the gas behind the

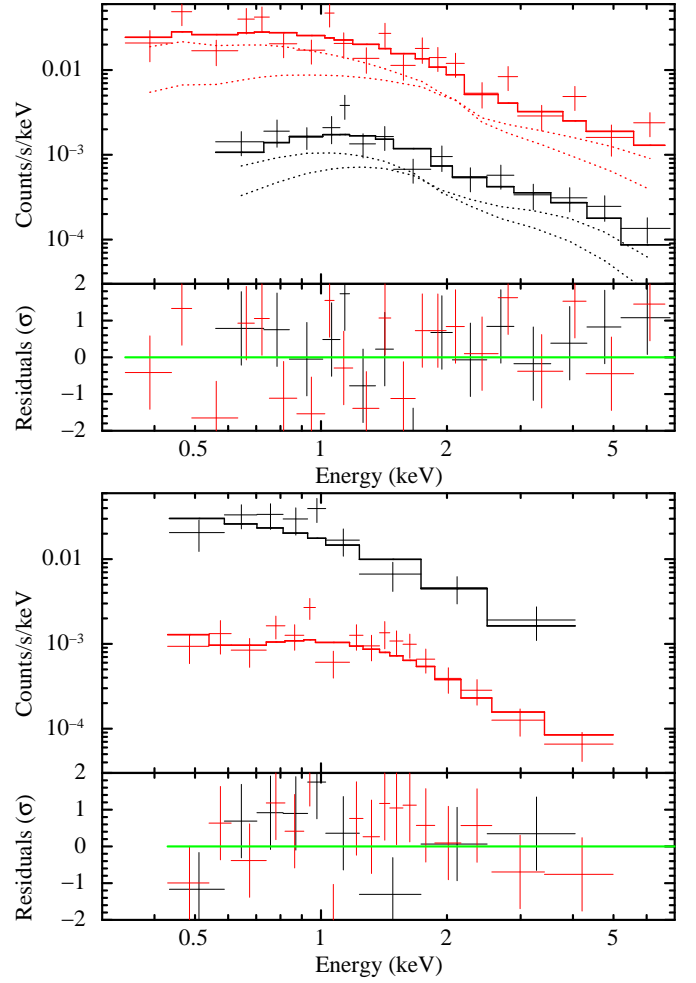


Fig. 3. X-ray spectra of SN 2011dh: stacked *Swift* spectrum for $t < 10$ d (Swift1, black in the *upper* diagram), *XMM-Newton* EPIC-pn spectrum taken at $t \approx 7$ d (XMM1, red in the *upper* diagram), *XMM-Newton* EPIC-pn spectrum taken at $t \approx 11$ d (XMM2, black in the *lower* diagram), and stacked *Swift* spectrum for $11 < t < 30$ d (Swift2, red in the *lower* diagram). The spectra in the *upper* diagram are fitted with a combined power-law + bremsstrahlung spectrum, while the spectra in the *lower* diagram are fitted with a power-law spectrum only. The *Swift* spectra appear at lower countrate per energy bin due to lower effective area of the detector.

reverse shock is cooler ($\sim 1 - 10 \text{ keV}$ Immler 2003). Hence a likely explanation for the softening of the X-ray spectrum is that the reverse shock emission becomes more dominant.

The analysis of the *XMM-Newton* EPIC-pn and *Swift* XRT spectra of SN 2011dh have shown that the X-ray spectrum changes during ~ 10 d after the SN event. If we assume that the longer persistent X-ray emission component can be interpreted as thermal bremsstrahlung, we obtain a temperature of $\sim 3 \text{ keV}$ after $t \approx 11$ d, i.e., $\sim 3 \times 10^7 \text{ K}$, corresponding to a shock velocity of $\sim 1500 \text{ km s}^{-1}$, which is far lower than what was measured in the optical spectra at these times ($\sim 10000 \text{ km s}^{-1}$, Arcavi et al. 2011b). Therefore, this component is better to be identified as reverse shock emission or IC emission. In this case, the additional hot component observed only until ~ 10 d after the SN event might be emission from circumstellar gas shocked by the forward shock.

A similar X-ray emission was also detected for SN 1993J with ROSAT few days after the SN explosion, which occurred in the galaxy M 81 at a distance of 3.6 kpc (Zimmermann et al. 1994). This emission was fitted well with a power-law spectrum with $\Gamma = 1.0 \pm 0.25$ or a bremsstrahlung spectrum with $kT_{\text{brems}} > 7$ keV, and decreased exponentially during the ~ 40 d in which it was observed.

Assuming free-free emission for the hard component, we obtain a lower limit for the temperature of $kT_{\text{brems}} > 42$ keV. The flux at $t = 7$ d is $F_{\text{brems}}(0.3 - 8.0 \text{ keV}) = (1.1 \pm 0.5) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$, corresponding to $L_{\text{brems}}(0.3 - 8.0 \text{ keV}) \approx 9.3 \times 10^{38} \text{ erg s}^{-1}$. Using the lower limit for the temperature, we obtain a lower limit for the shock velocity of

$$v_s = \sqrt{\frac{16kT_{\text{brems}}}{3\bar{m}}} > 9800 \text{ km s}^{-1}, \quad (1)$$

with a mean mass per free particle for fully ionised plasma of $\bar{m} = 0.61 m_p$. Soderberg et al. (2012) estimated $v_s \approx 0.1 c$, which is about three times higher than this lower limit. The *XMM-Newton* and *Swift* spectra that only extend up to ~ 10 keV do not allow to constrain the temperature for a bremsstrahlung model. Using $v_s \approx 0.1 c$ derived by Soderberg et al. (2012), we estimate that at $t = 7$ d, the shock must have reached a radius of $R_s \approx v_s t \approx 1.8 \times 10^{15} \text{ cm}$. Therefore, from the bremsstrahlung spectrum at $t = 7$ d, we derive a down-stream density of $n = 6.4 \times 10^7 \text{ cm}^{-3}$ at $R_s \approx 1.8 \times 10^{15} \text{ cm}$.

On the other hand, we can also estimate the stellar wind density based on assumption of the progenitor star. SN 2011dh was classified as a type IIb SN with a compact progenitor, making a Wolf-Rayet (WR) star a likely progenitor candidate (Chevalier & Soderberg 2010). The number density of the wind at a distance r from the WR star is given by the continuity equation:

$$n(r) = \frac{\dot{M}}{4\pi\mu m_p r^2 v(r)} \quad (2)$$

where \dot{M} is the mass-loss rate, μ is the mean atomic weight of the wind material, and $v(r)$ is the β -velocity law (Castor et al. 1975):

$$v(r) = v_\infty \left(1 - \frac{bR_*}{r}\right)^\beta. \quad (3)$$

R_* is the stellar radius, v_∞ the terminal velocity, $b = 0.9983$ a parameter that ensures that $v(R_*) > 0$, and $\beta = 4 - 8$ for WR stars (Schmutz 1997). The volume integral of equation (2) over a shell with radii R_{br} and R_s centered at the position of the WR star gives the total number of particles:

$$N = \int_V n(r) dr. \quad (4)$$

Thus, from equation (4), it is possible to obtain the average number density in that shell:

$$\bar{n} = N \times \left[\frac{4}{3} \pi (R_s^3 - R_{\text{br}}^3) \right]^{-1}. \quad (5)$$

Soderberg et al. (2012) estimated a stellar radius of $R_* = 10^{11} \text{ cm}$, a shock break-out radius of $R_{\text{br}} = 4 \times 10^{11} \text{ cm}$, and a mass loss rate of $\dot{M} = 3 \times 10^{-5} M_\odot \text{ yr}^{-1}$. With a typical wind velocity of $v_\infty = 10^3 \text{ km s}^{-1}$ and $R_s = 1.8 \times 10^{15} \text{ cm}$ at $t = 7$ d, we obtain a mean stellar wind density of $\bar{n} \approx 8 \times 10^5 \text{ cm}^{-3}$ from equation (5). This calculation is based on the assumption, that

the stellar wind density is highest close to the stellar surface and decreases with $\sim r^{-2}$. However, the stellar wind material might as well form a dense shell around the star at a certain distance, as was most likely the case for SN 2006jc (Immler et al. 2008). This SN showed an increase in X-rays about 100 days after the explosion which was interpreted as emission from shock heated shell at $R_s \approx 10^{16} \text{ cm}$ with a thickness of $\Delta R \approx 2 \times 10^{15} \text{ cm}$. A similar condition might have been the case also for SN 2011dh, however, with a shell being located closer to the star, which resulted in an earlier rise and decay of the X-ray emission.

5. Summary

Two *XMM-Newton* observations of SN 2011dh performed ~ 7 and 11 days after the discovery revealed that the X-ray spectrum changes significantly at about 10 days after the explosion. The analysis of the *XMM-Newton* EPIC-pn spectra and additional stacked *Swift*/XRT spectra extracted from many observations of similar periods supports the existence of two spectral components with the harder component disappearing after ~ 10 days. The softer component can be identified either as IC emission as suggested by Soderberg et al. (2012) or as reverse shock emission with an unabsorbed flux of $F_{\text{soft}}(0.3 - 8.0 \text{ keV}) \approx 1 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ up to $t \approx 30$ d. The flux of the hard component if we assume that it is bremsstrahlung emission, is $F_{\text{brems}}(0.3 - 8.0 \text{ keV}) = (1.1 \pm 0.5) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ at $t = 7$ d, and thus comparable to the soft component, and decreases quickly thereafter. This indicates that this emission has its origin in the circumstellar matter that extends to $\sim 10^{15} \text{ cm}$ and was heated by the SN shock.

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